

# A Boresight Adjustment Mechanism For Use on Laser Altimeters

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## Abstract

This paper describes the development of the Boresight Adjustment Mechanism (BAM) for the Geoscience Laser Altimeter System (GLAS) Instrument. The BAM was developed late in the integration and test phase of the GLAS instrument flight program. Thermal vacuum tests of the GLAS instrument indicated that the instrument-boresight alignment stability over temperature may be marginal. To reduce the risk that GLAS may not be able to meet the boresight alignment requirements, an intensive effort was started to develop a BAM. Observatory-level testing and further evaluation of the boresight alignment data indicated that sufficient margin could be obtained utilizing existing instrument resources and therefore the BAM was never integrated onto the GLAS Instrument. However, the BAM was designed fabricated and fully qualified over a 4 month timeframe to be capable of precisely steering ( $< 1$  arcsec over  $\pm 300$  arcsec) the output of three independent lasers to ensure the alignment between the transmit and receive paths of the GLAS instrument. The short timeline for the development of the mechanism resulted in several interesting design solutions. This paper discusses the requirement definition, design, and testing processes of the BAM development effort, how the design was affected by the extremely tight development schedule, and the lessons learned throughout the process.

## Introduction

The GLAS instrument was successfully launched aboard the Ice, Cloud, and Land Elevation Satellite (ICESat) into a near polar orbit on January 12, 2003. NASA's ICESat will accurately measure the height of the earth's polar ice masses, land and ocean surfaces using the advanced precision 1064-nm laser altimetry technology of the GLAS instrument<sup>1</sup>. The instrument also uses 532-nm LIDAR to measure clouds and aerosols in the atmosphere<sup>2</sup>. ICESat was designed to operate for 3 to 5 years.

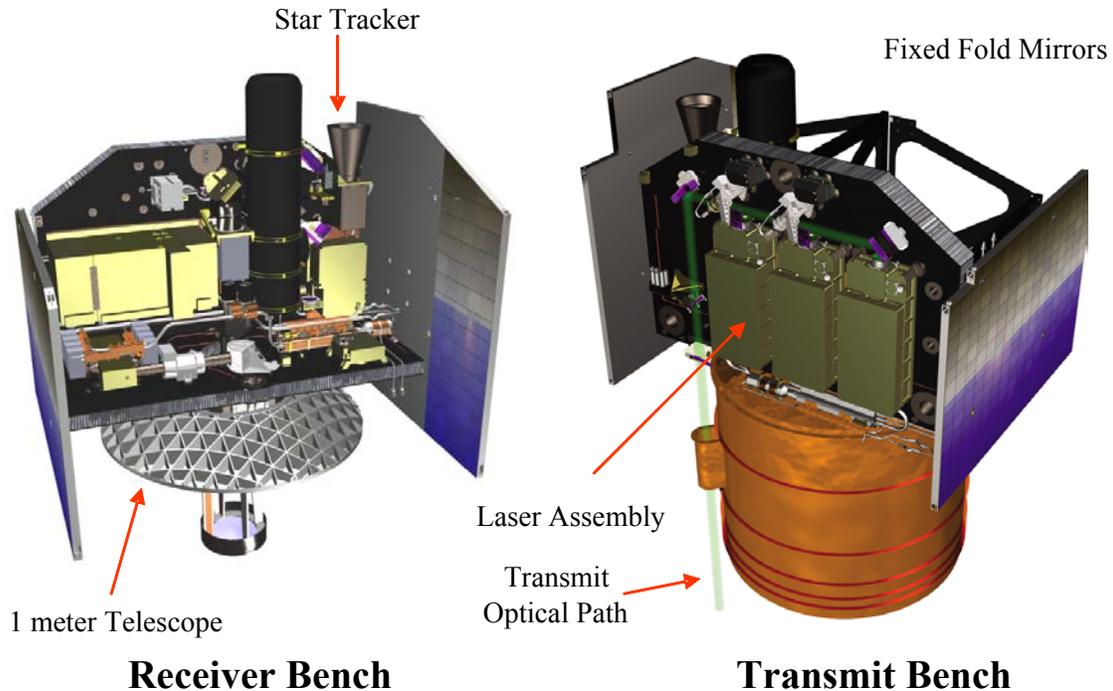
The GLAS receive path (Figure 1) consists of a 1-meter-diameter beryllium telescope, and an aft-optics assembly which splits the incoming reflected laser signal into 2 beams by wavelength, 532 nm and 1064 nm. The 532-nm LIDAR beam is directed onto a fast steering mirror, through an etalon filter, and into an array of 8 single-photon counting modules. The 1064-nm altimetry channel is directed into the primary altimeter detector assembly or shunted via a flip mirror mechanism, (the Altimeter Detector Select Mechanism or ADSM<sup>3</sup>) into the redundant altimeter assembly.

A view of the laser transmit path is shown in Figure 1. The laser transmit path uses one of three Nd:YAG 4-watt lasers, each producing a 25-mm x 25-mm square beam. The lasers are used one at a time, and all fire along a common beam path<sup>2</sup>. The first laser, Laser 1, fires until it fails. The on-orbit laser lifetime is projected to be approximately 18 months. Laser 1 reflects off a fixed fold mirror and is directed to a second fixed fold mirror. The laser beam then passes through a pick-off mirror and exits the instrument along the transmit path boresight. The pick-off mirror re-directs a small portion of the laser energy into the Laser Reference System, which monitors laser output and provides precision beam pointing knowledge. Lasers 2 and 3 can be selected via precision flip mirrors, which are deployed into the optical path by the Laser Select Mechanisms (LSM's)<sup>3</sup>. In the case of a laser being powered on out of sequence, beam dumps provided safety for the instrument detectors, personnel, and the lasers themselves. The individual optical alignment and stability requirements placed on these transmit path components were extremely tight, with  $< 5$  arcsec stability over a 30 °C temperature range.

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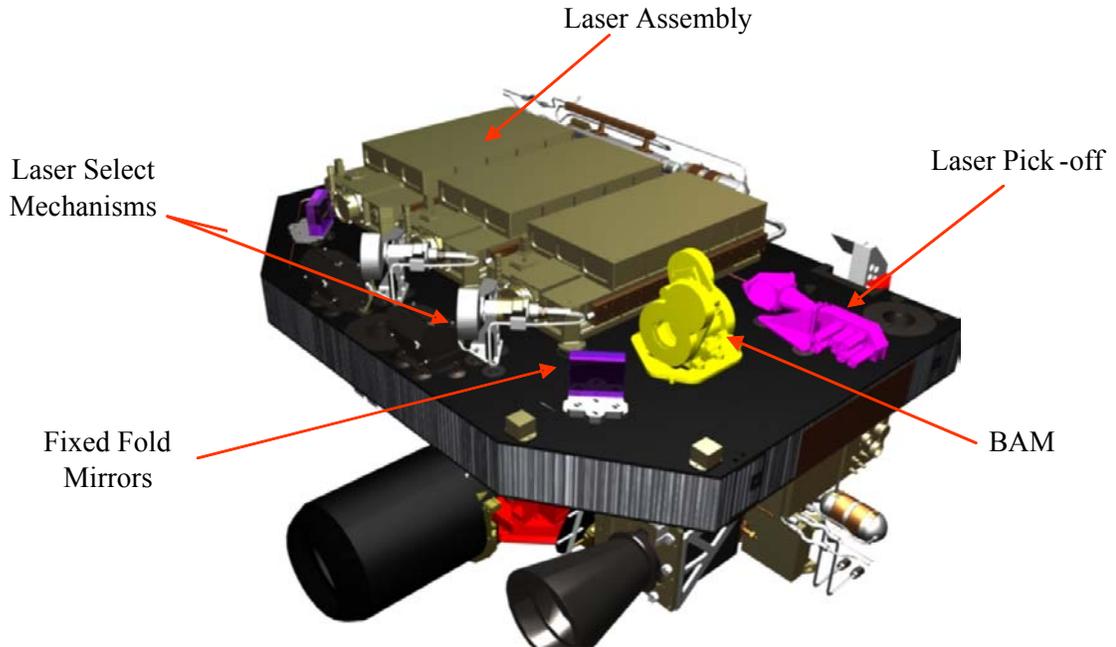
The boresight alignment between the transmit path and the receive path is critical to the performance of the GLAS instrument. The alignment requirement between the transmit and receive paths was <30 arc seconds for full science, and <42 arcseconds for 50% (FWHM) response. The 50% response is considered the minimum acceptable range for science. These alignment requirements had to be met pre-launch to post launch, and within a thermal range of 15°C to 23° C<sup>5</sup>



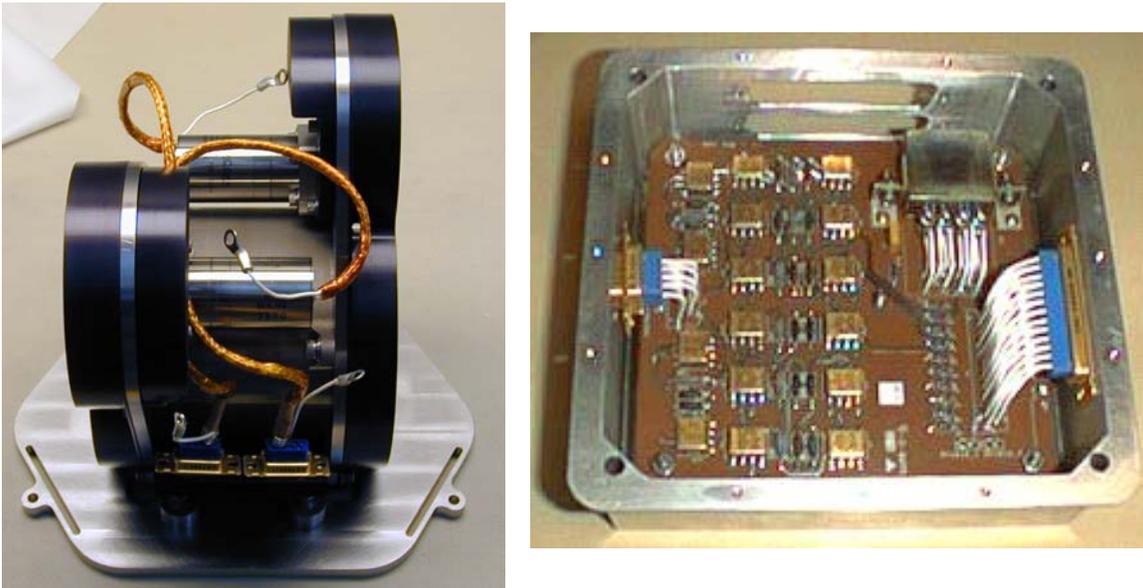
**Figure 1. GLAS Receiver and Transmit Bench**

Since testing indicated that the boresight alignment over temperature may be marginal, it was decided to pursue rapid development of a Boresight Adjustment Mechanism. This effort, in parallel with continued environmental testing of GLAS, was intended to mitigate potential marginal alignment performance should further tests and data reduction indicate that the GLAS instrument was failing to meet its alignment budgets. Final testing and data reduction later indicated that the boresight alignment and stability budgets could be maintained using existing instrument resources. At that time, it was determined that the integration of the BAM onto the GLAS instrument was not required. The BAM would have been mounted as shown in Figure 2 had it been integrated into the GLAS instrument.

The operating principle, requirements, design, and testing of the BAM are described. The BAM was developed over a 4-month period. During that time a proto-flight mechanism, flight electronics, spare electronics, and ground support equipment were designed, fabricated, and fully flight qualified. Photographs of the BAM and the BAM Electronics (BAME) are shown in Figure 3. The BAM utilizes two motorized counter-rotating prisms to precisely steer the incoming laser radiation. This configuration is commonly referred to as a risley pair. This simple, yet precise, beam steering technique was the baseline for the BAM.



**Figure 2. Proposed BAM Location on GLAS Laser Transmit Bench**



**Figure 3. Photos of the BAM and the BAME**

Operating Principle (Risley Pair Equations)

The angular deviation  $\delta$  of a beam passing through a single prism is given by:

$$\delta = \alpha(n - 1)$$

Where  $\alpha$  = prism angle and  $n$  = refractive index of prism

If the prism is rotated about the incoming beam axis, the beam is rotated, forming a conical scan pattern of half angle  $\delta$ . If the beam is then passed through a second identical prism, the subsequent deviation provides a second degree of freedom. This allows for a variety of scan patterns, including linear scans. The net angular deviation of a beam passing through a pair of identical prisms is the sum of the two individual prism angular deviations. We define angular beam deviation about two orthogonal axes as  $\delta_x$  and  $\delta_y$ . Thus the deviation of a beam passing through a pair of identical prisms at arbitrary rotational positions can be defined as:

$$\delta_x = \delta \cos(A_1) + \delta \cos(A_2) \quad \delta_y = \delta \sin(A_1) + \delta \sin(A_2)$$

Where  $A_1$  = rotational position of first prism and  $A_2$  = rotational position of second prism

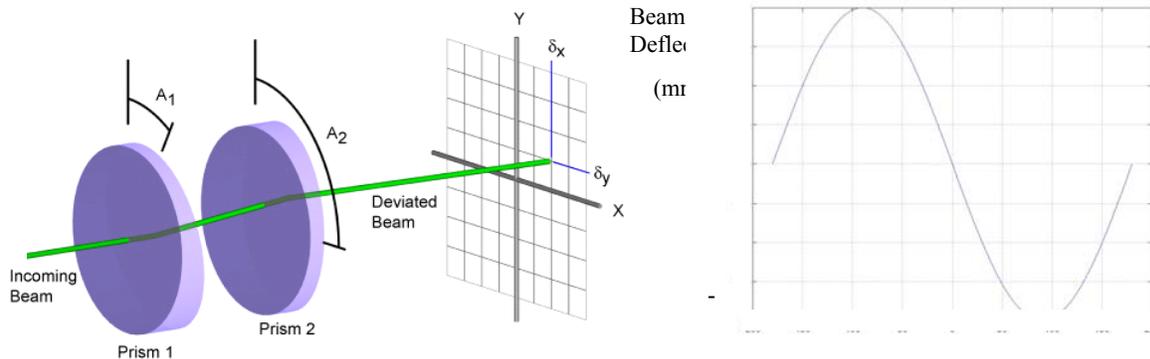
If  $A_1 = -A_2$ , a linear scan along the X axis is realized,  $\delta_y = 0$

If  $A_1 = 90^\circ - A_2$ , a linear scan of slope 1 is realized,  $\delta_x = \delta_y$

If  $A_1 = 180^\circ - A_2$ , a linear scan along the Y axis is realized,  $\delta_x = 0$

For continuous maximum deviation of  $2\delta$ :  $A_1 = A_2$

For continuous minimum or nulled (zero) deviation:  $A_1 = A_2 + 180^\circ$



**Figure 4. Risley Prism Principle and Theoretical Beam Deviation**

The maximum angular deviation of the prism pair is  $2\delta$ . Therefore, only the prism angle,  $\alpha$ , and index of refraction,  $n$ , determine the stroke of a risley prism pair scanner. Errors in deviation occur if the prism angles or index of refraction are not perfectly matched. Differences in  $\alpha$  or  $n$  of the prisms result in small linear variations of  $\delta$ . Angular resolution within the stroke is limited only by rotational positioning resolution of the individual prisms.

#### Operation

Whenever the wedges are aligned such that the wedge angles are  $180^\circ$  out of phase, then incoming radiation is not deviated. This is called a nulled position of the prisms. When the prisms are counter rotated from this position the incoming laser radiation is then deviated depending on the amount of counter rotation and the wedge angle present on the prisms. The beam deviation is along a line that is parallel to the null position of the wedges. Therefore, in order to sweep out a cone it is required to first define the nulled position angle and then counter rotate the prisms to move along this angle to deviate the incoming radiation. The risley prism principle of operation and the theoretical optical beam deviations given the parameters of the prisms used in the BAM are shown in Figure 4.

The critical factor defining pointing resolution is matching the geometric and optical properties of each prism. Risley pairs have several desirable attributes as applied to precision pointing of lasers or other refractive systems:

(1) Precise angular steering (2 arcsec or better) is possible without precision location or alignment of the supporting mechanism structure.

- (2) The individual alignment requirements of the rotating prisms relative to each other are loose.
- (3) Large opto-mechanical advantage can be obtained depending on the wedge angle and index of refraction of the individual prisms.

The BAM utilized risley pairs that were already fabricated for the Laser assemblies. The laser risley pairs were used to complete a static alignment of the laser assemblies to the transmit path and were adjusted manually. Due to the long lead times required for precision matched risley prism pairs, the rapid BAM development (< 4 months) could probably not have been achieved if spare matched risley pairs were not available.

### Requirements

In order to not affect the GLAS schedule, the development of the BAM could have no impact on the testing of the GLAS instrument. All resources required and requirements developed for the BAM must be consistent with this non-interference requirement. The BAM had to be developed utilizing only "spare" resources of the spacecraft and instrument. Based on the amount of possible boresight misalignment and resources available, the GLAS science team, with inputs from the engineering team, developed the following requirements for the BAM:

#### Environmental and Resource Requirements

- Volume: < 22.9 cm (9") high, 17.8 cm (7") wide, 20.3 cm (8") long
- Mass: < 5 kg
- Power: < 13.5 watts peak, < 5 watts average
- Vibration: Sine Burst: X 9.75 g, Y & Z; 5 g  
Random: ~ 7 GRMS X, Y, & Z axes
- Vibration: Minimum Resonant Frequency >100 Hz
- Thermal: -25°C to +40°C Survival, 0°C to 30°C Operation
- Thermal: < 30° C rise (30 minute operation, 60 minutes to cool)
- Duty Cycle: 12 alignment sequences (<50K motor revs.)
- Contamination Levels: 100 A
- Magnetic Leakage: < 10 milligauss @ 30 cm
- EMI/EMC Tested to Spacecraft Specification

#### Optical Requirements

- Beam Adjustment Range: 0.75 milliradians
- Beam steering precision: 30-50 microradians
- Wedge Physical Diameter: 5.4 cm (2.126") Existing Wedge Spares
- Risy Rate (Linear): 35 microradians/degree
- Clear Aperture: < 5.1 cm (2") existing optics
- Launch Stability: < 10 microradians
- Wedge Angle: 0.127 ± .005 degree Existing Wedge Spares
- Thickness: 0.55 cm (~0.217") Existing Wedge Spares
- Optical Axis to Bench: 6 cm (2.360") As built
- Rotational Rate: 180°/minute desired, but not critical  
(achieved 50°/minute, deemed acceptable)
- Stability over observation: < 20 microradians (4 arcsec.)
- Stability Observation to Observation: < 20 microradians (4 arcsec.)
- Knowledge of Rotation: 0.6 ± 0.05 degree (by counting motor steps)
- Relative Rotational Accuracy: 0.6 ± 0.05 degree (by counting motor steps)
- Prism to Prism Gap Tolerance: Limited by Clear Aperture
- Allowable element Tilt: <10 degrees
- Allowable Assembly Tilt: Rx and Ry = 5 degrees, Rz is Controlled
- Allowable element shear: Limited by Clear Aperture

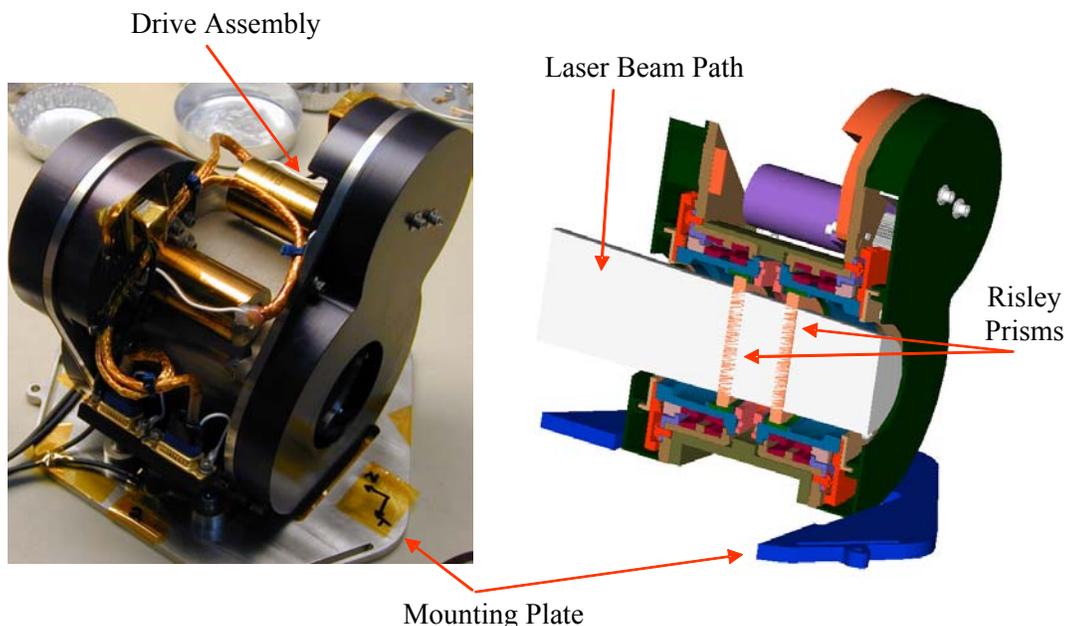
#### Electrical

BAM Electronics (BAME) Requirements

- Drive the 2-Phase stepper motors on the BAM
- No resources available from the GLAS instrument
- Commanding limited to using spare High Level Discrete Command (HLDC) lines from spacecraft
  - Each HLDC is a commandable solid state relay output
  - Only one HLDC can be high at a time
  - Logic high = +24 to +31V      Logic low = high impedance
  - Fixed 50 ms  $\pm$  5 ms pulse width with rise and fall time  $>1 \mu\text{sec}$  and  $<10 \mu\text{sec}$
  - Maximum of 10 Hz command rate
  - Maximum current per command line 280mA
- Additional power available from spare laser heater supply circuit: +30V, 28 watts peak
- No telemetry available
- Must provide 100% electrical isolation from motor when not operating
- Electronics Box Mass:  $<2 \text{ kg}$
- Harness length:  $>3 \text{ m}$  and  $<10 \text{ m}$
- Design using available spare flight approved parts from other GSFC programs

### Mechanism Description

The BAM assembly is composed of the following components: the mounting plate, the main structure and two identical prism drive assemblies. The drive assemblies are mounted back to back on either side of the main structure. Each drive assembly supports one of the risley pair prisms on the inner diameter of the rotating shaft. The laser radiation travels through the center of the BAM as defined by the rotational axes of the shafts. Figure 5 shows a photograph and a cross-section of the BAM. Each drive assembly independently rotates the respective prism via a spur gear that meshes with the output pinion of the stepper motor actuators. The main structure was bolted to the mounting plate through a shimmed 3-point mount to provide centerline to mounting plane height adjustment capability.



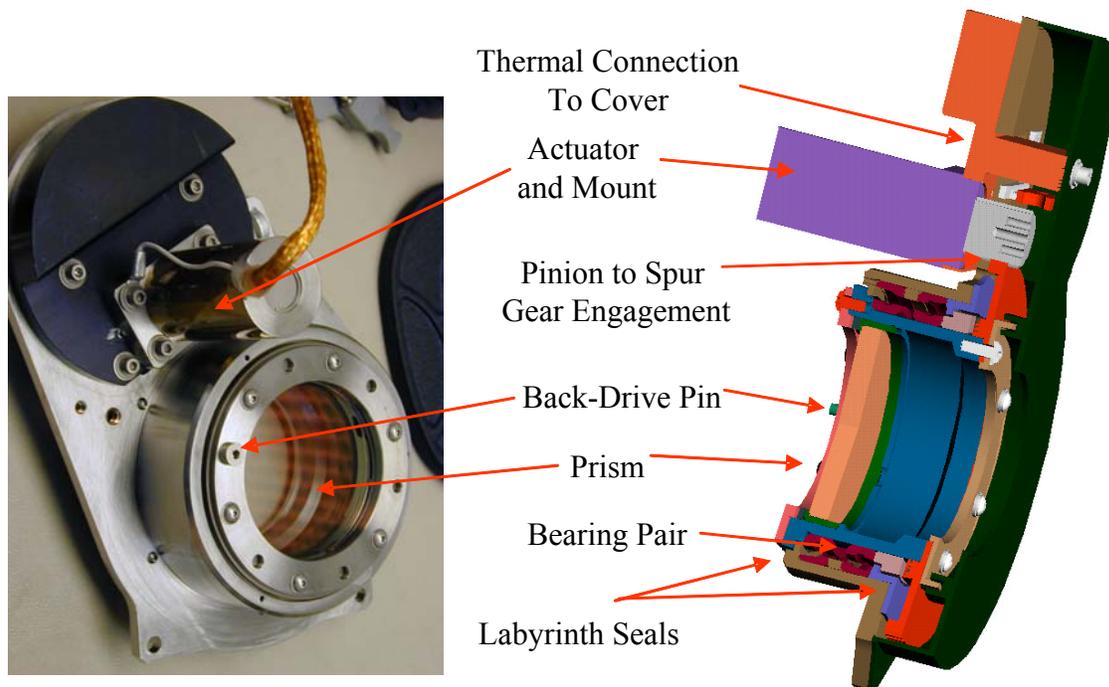
**Figure 5. BAM Photograph and Cross-Section**

The main structural components of the BAM, the mounting plate, main housing, and bearing housings were made of Titanium Ti6Al4V. This material provided a good CTE match to the bearings and compliance flexures cut into the mounting plate provided ample margin for the CTE mismatch between the BAM plate and composite optical bench. Since the BAM would have been attached after the fact,

Click-bonds (#10-32 studs) were to be adhesively attached to the optical bench. The compliance in the mounting plate was sized to maintain the minimum resonant frequency requirement and also to ensure that thermally induced stresses would remain well below the allowable stress calculated for the Click-bond to composite structural adhesive bond. The titanium did present a thermal problem since maximum thermal gradient requirements had been established for the BAM due to the close proximity of the mechanism to the laser assemblies. The actuators were mounted to Aluminum 6061-T6 motor housings that were thermally coupled directly to the aluminum cover. The housings and the cover act as radiators to the interior of the GLAS instrument and represent the primary transfer path to shed heat from the actuators. The motor housings also incorporated additional mass to increase the thermal time constant and minimize the maximum temperature experienced under operating conditions.

#### Drive Assembly Description

A cross-section and photograph of the BAM prism drive assembly are shown in Figure 6. It consists of the following components: stepper motor actuator and mount, GSE step verification sensor, bearing housing, angular contact ball bearings and preload spring, spur gear, shaft, risley prism assembly and preload spring, and gear cover. The risley prism is preloaded within the rotating shaft, which is driven by the actuator thru a spur gear attached to the outboard end of the shaft. The shaft is supported by angular contact ball bearings which are outboard of the risley prism outer diameter and are preloaded in a back to back configuration into the drive assembly housing via a custom designed wave spring. Labyrinth seals were utilized on either side of the bearing pair and between the spur gear and gear cover to minimize potential contamination. Photographs of selected components of the BAM during the assembly of the mechanism are shown in Figure-7



**Figure 6. Drive Assembly Cross-section and Photographs**

#### Drive Train

The drive train consisted of a stepper motor actuator and spur gear. The actuators were obtained from CDA Intercorp. They were 30° stepper motors with a two stage, 50:1 planetary gear reduction. They incorporated a custom mounting flange and an integral output pinion. The spur gears were obtained from PIC and were modified to allow alignment and attachment to the drive assembly shaft. The gear also acted to compress the bearing preload spring when bolted to the shaft. The 303 SS gear provided the additional 264:38 gear reduction. Combining the risley rate of 35 microradians/degree of counter-rotation,

the 30° steps of the stepper motor, and the planetary/spur gear reductions, each motor step resulted in ~0.6 arcsec of beam deviation.

Torque margin was measured by determining the minimum voltage at which the mechanism would still step consistently during the thermal vacuum testing of the mechanism at both temperature extremes. It was determined that the BAM/BAME could be operated with voltages as low as 6V under worst-case beginning of life conditions. Given the nominal operating voltage of +30V, this margin was deemed sufficient for this relatively low duty cycle application. During the test program over 80,000 steps were logged on the actuators without incident.

Although there was no redundancy requirement placed on the BAM, a failsafe feature was incorporated into the design that would allow for continued operation of the BAM given the failure of one of the drive assemblies. Backdrive pins protrude from the inner surfaces of the rotating shafts of each drive assembly. They overlapped in the axial direction such that if one drive assembly continued to rotate it would engage the pin of the second drive assembly thus backing driving the second drive assembly. It would therefore be possible to rotate both wedges to any desired position. In addition, if for any reason the orientation of the two prisms relative to each other was in doubt, the back driving pins could be used to re-establish a known relationship between the prisms.

#### Prism Mounts and Preloading

The prism assemblies were taken as a “qualified” assembly. The fused silica prisms are bonded into an invar ring. These assemblies were preloaded and locked in rotation by a custom designed titanium wave spring. The spring provided axial preload of the prism cell to the shaft while also engaging angular slots in both the cell and the capture ring to ensure that the prism could not rotate relative to the shaft.

#### Bearings and Lubrication

The ball bearings (MPB # 4050) were 440C stainless angular contact ball bearings mounted in a back to back configuration with a spacer between the outer-races and were preloaded with a custom designed titanium wave spring applying 133 N (~30 lb) to the inner race. They were cleaned post delivery and lubricated at GSFC using Braycote 815z oil and 601 grease. The output pinion and spur gear were also lubricated with a light coating of the same lubricant. This lubricant was selected primarily for its low outgassing characteristics and availability. The actuator was also lubricated with the same lubricant by the vendor. An anti-wetting coating was applied to critical surfaces to inhibit creep of the lubricant to unwanted surfaces. Great care was taken to ensure that no lubricant came in contact with the prism assemblies or any surfaces they interface with. There was concern that the high-energy laser radiation may breakdown the lubricant and either reduce optical throughput or cause failure of the coatings applied to the prisms which could prove to be a catastrophic failure of the laser transmit path. The transparency of Braycote to the wavelengths of light in question was investigated but it was determined that the effects of the high energy radiation on the lubricant were unknown. The same lubricant was also utilized in the laser assemblies, which had even more stringent contamination requirements.

#### GSE Sensors

Two sensors were incorporated into the BAM for ground testing purposes. The BAME had no available telemetry, so the sensors were operated and monitored using Ground Support Electronics (GSE). A magneto-resistive sensor was placed in proximity to the output pinion of each of the actuators. The pinions were made of a soft magnetic material. As the teeth of the pinion passed by the sensor, the variations in the gap were sensed and recorded. The resolution of the sensors provided an easily visible response for each and every step taken by the motors. This valuable data was used to verify that the motor never missed steps during characterization, thermal vacuum, and EMI/EMC testing as well as provided a means of determining torque margin. Although there is no reason that this sensor could not have flown, the plan was to remove it prior to flight.



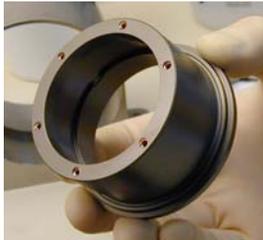
Mounting Plate  
Compliant



BAM Structure and  
Assembly



Bearing  
(OD of Bearings)



Drive Assembly



Shaft Inserted into  
Bore w/ Preload Wave



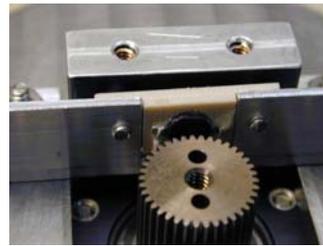
Modified Spur



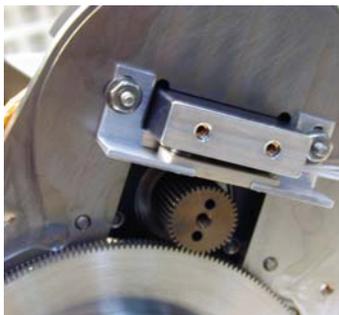
Bearing Preload  
Assembly



Actuator in  
Motor



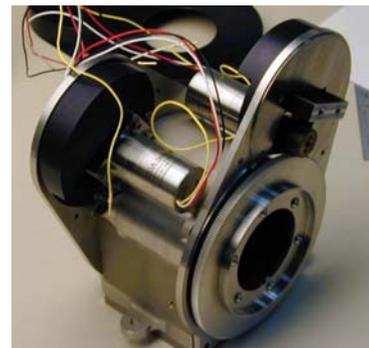
GSE Step  
Sensor



Pinion to Spur  
Engagement



Housing w/ One  
Assembly



Preliminary BAM Assembly  
(No Cover or Mounting)

**Figure 7. BAM Assembly**

### BAME Design and Operation

Given the limitations in time, parts, and command capability, the BAME design had to be as simple and reliable as possible. A latching, mechanical relay (part# JL-D2A-108) was included to completely isolate the BAME from the spacecraft bus when not being operated. Using one HLDC to close and one HLDC to open the latching relay, the BAME was connected or isolated from the spare laser heater power line providing a peak power capability of 28 watts. Other HLDCs were used to drive optically coupled solid state relays (part# HSSR-7111) in an H-bridge configuration to drive current in each phase of each motor (Figure 8). Each separate HLDC was a unique commutation state for one of the two BAME motors. By sequencing the HLDCs, each motor could be commanded one step at a time clockwise or counter-clockwise with a 50-msec pulse at a maximum rate of 10-Hz. Since only one HLDC could be activated at a time, the H-bridge could not inadvertently be shorted by commanding a node high and low simultaneously. The inputs diodes of the relays only required between 5 mA and 20 mA each, so the HLDC limit of 280 mA provided ample margin to drive two at a time. Each motor coil was about 60 ohms, so using the +30-V supply, a maximum current of 0.5 A was drawn at any time. The solid state relays and spacecraft heater power lines were rated to supply 1 A, so the BAME had 50% derating for those components. All of the BAME parts, including associated resistors and capacitors, were spare flight parts primarily left over from the TRIANA project. Even the enclosure was a flight qualified leftover from the Shuttle small payloads program. The biggest limitations were no telemetry was available and no memory resided on the BAME. The boresight alignment information had to be determined by the GLAS pick-off and each motor's commutation state had to be tracked by the spacecraft ground ops. However, the proposed operation of the BAME could easily accommodate these issues and provide an excellent means of fine tuning the GLAS boresight alignment at any point during the mission.

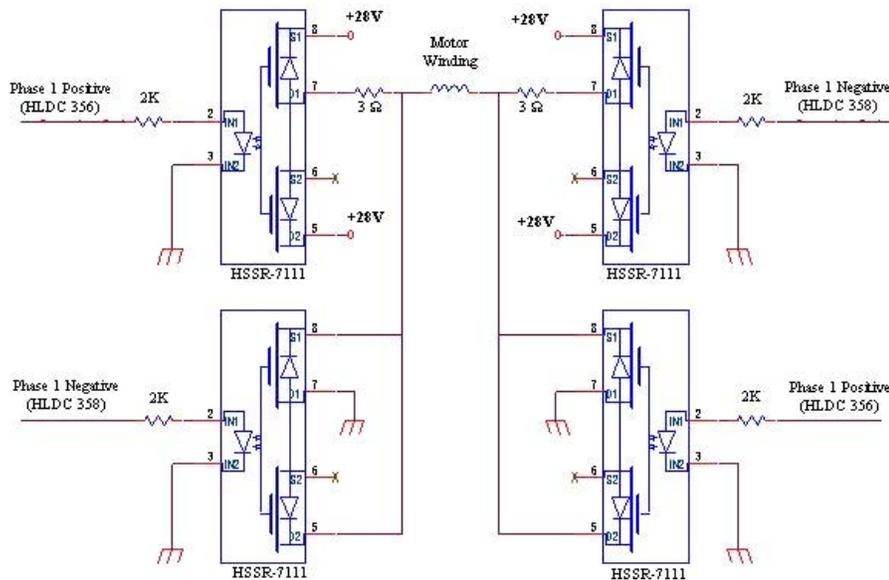


Figure 8. Simplified Schematic of H-Bridge Driver – One Motor Phase

## Verification and Test

Although the development schedule for the BAM was extremely tight, all phases of the review/verification process were completed. The design of the BAM was subjected to preliminary and critical design reviews and a post environmental testing delivery review. Analysis of all critical components was performed to evaluate margins for performance and strength. The BAM was subjected to baseline performance testing (beam deviation and torque margin), protoflight vibration testing, thermal vacuum cycling and performance testing, EMI/EMC, magnetic leakage, and post environmental performance testing. The BAM successfully passed all verification tests. During the testing program the BAM executed >80,000 motor steps which is approximately 1.6 times the expected on orbit lifetime.

### Vibration Testing

The Bam and the BAME were both subjected to protoflight random and sine burst vibration levels at the GSFC. Both components passed the tests. Post-test inspection of the BAM did raise some concerns. A chip on the edge of one of the risley prisms was “discovered”. It was determined that the chip was probably present prior to vibration. Further discussion of this event is given in the lessons learned section.

### Thermal Vacuum Testing

The BAM and BAME were tested simultaneously in the same chamber using two separate cold/heater plates. The performance of the system was verified over the operating and survival temperature ranges. Figure 9 shows a schematic of the thermal vacuum test set-up. The units were subjected to a minimum of ten hot-to-cold operating cycles and two hot-to-cold survival cycles. This test lasted approximately 2 weeks. Torque margins were measured for the worst-case conditions utilizing the GSE step counter sensor. Behavior of the system with the BAME hot and the BAM cold and vice versa was characterized. The BAM and BAME were instrumented with thermal couples on critical components to characterize the thermal behavior of the units. A typical thermal profile during continuous operation of the BAM is shown in Figure 10 along with a photo of the BAM in the thermal vacuum chamber. In addition, outgassing data was collected by witness samples and a cold finger to verify the cleanliness of the units.

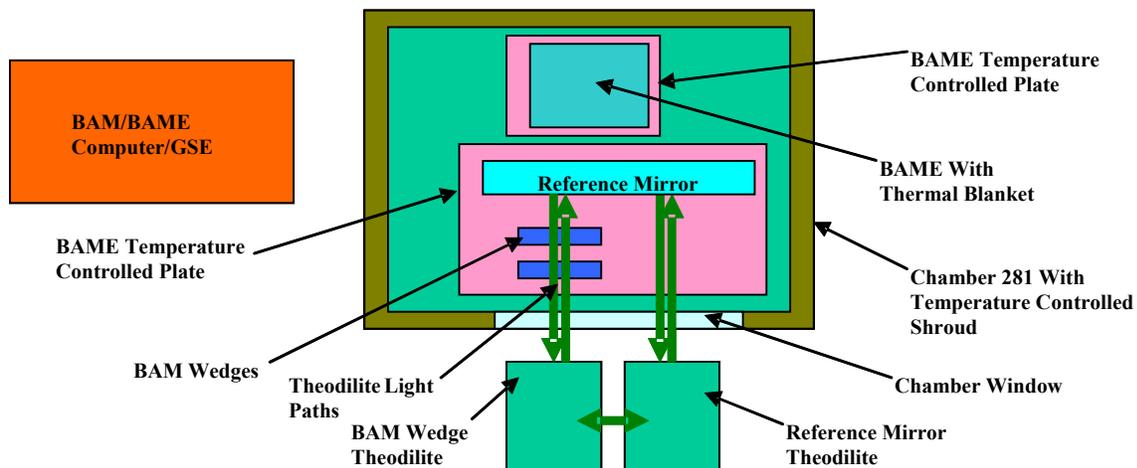
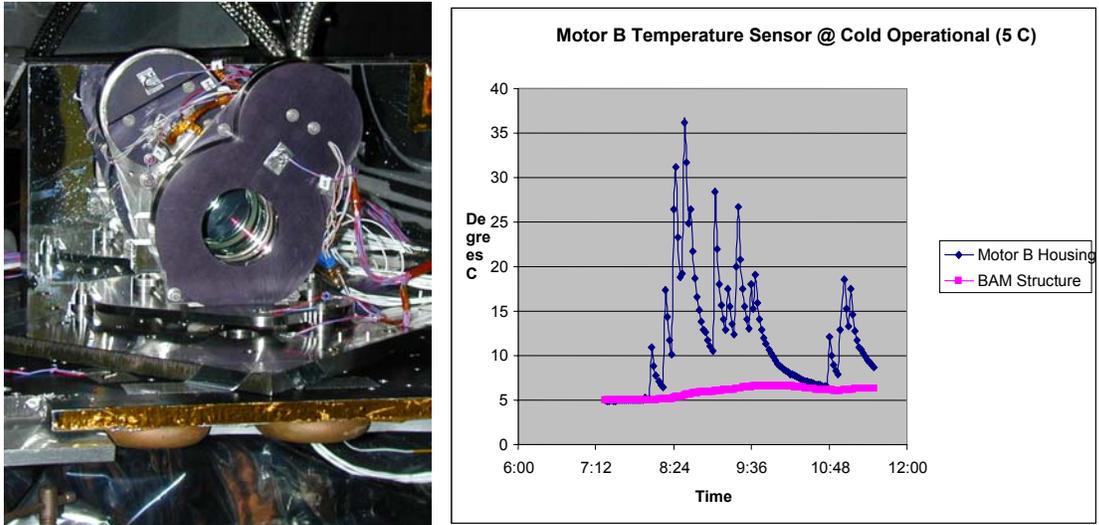


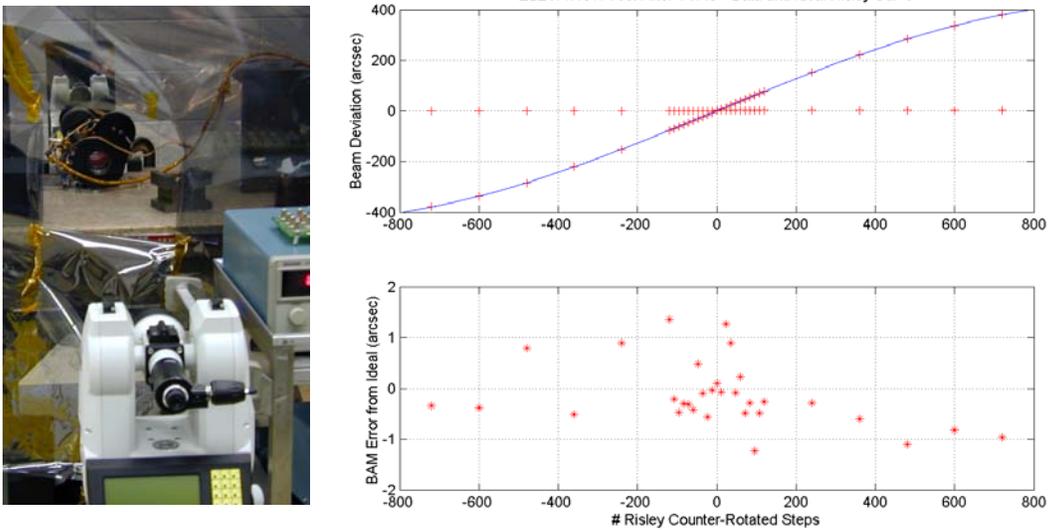
Figure 9. Thermal Vacuum Testing Setup



**Figure 10. Characterization of Thermal Behavior During BAM/BAME Thermal Vacuum Testing**

Performance

The performance test to characterize the beam steering capability of the BAM was accomplished using an auto-collimator in a double pass configuration. A large flat mirror was placed behind the BAM. The autocollimator was aligned to the reference mirror. As the risley prisms rotate the beam deviation was observed by the autocollimator. Since the BAM is only required to correct for possible boresight alignment errors on a seasonal basis no dynamic measurements were required. The same technique was also utilized during the thermal vacuum testing however an additional autocollimator was used to monitor the reference mirror through the thermal vacuum chamber window. Performance tests were conducted after assembly (to obtain a baseline) during the environmental testing, and post environmental testing. No degradation in performance was observed. Figure 11 shows a photograph of the basic test set-up and the actual beam steering capability as compared to the theoretical curve. It demonstrates that the performance of the BAM was within the measurement capabilities of the set-up.



**Figure 11. Performance Verification Setup and Elevation Axis Results (similar results for azimuth)**

## Lessons Learned

### Tailor requirements and design concepts for success

The utilization of the risley prism concept made it possible to develop a flight qualified precision boresight adjustment mechanism in <4 months. The alignment capability of the mechanism allowed loose installation alignment requirements and made the BAM a viable risk reduction option that could be implemented late in the I&T phase of the GLAS instrument. By thorough engineering and trade negotiations, we were able to tailor most of the BAM design requirements to readily available resources. We made our job as easy as possible while still meeting the goals of providing a precision mechanism to reduce the risk of marginal boresight alignment stability performance of the GLAS instrument. This lesson can and should be applied to every project at every phase of instrument mechanism development. Always look to ways that can reduce sensitivity and increase the robustness of a design.

### Photographs May Prove to Be Invaluable

The BAM utilized spare risley prisms from the laser assemblies. The paper work documenting the characterization of the prism assemblies was examined and the two closest matching prisms were selected for the BAM. Great care was taken not to contaminate the prisms as molecular or particulate contamination could be fatal to the transmission of the relatively high power laser radiation refracting through the prisms. After final assembly and baseline performance testing the protoflight unit was vibrated. The BAM assembly was inspected post vibration for any signs of potential failures. A chip was "discovered" in one of the prisms. The records of all of the spare risley prisms were investigated to determine whether the chip was pre-existing or a result of the vibration test. The documentation of the spare risleys was lacking. They were relegated to spare status because of less than perfect coatings or matches to other risleys. It was impossible to determine whether or not the chip had existed prior to vibration. After microscopic inspection of the area in question, and review of numerous photographs taken during the assembly and testing of the BAM, it was determined that there was evidence that the chip existed prior to vibration. Unfortunately, it had not been noted during the cursory visual inspections that were limited by the desire to minimize potential contamination of the prisms. A lesson learned here is to fully inspect "already qualified" or "spares" items and to take numerous pictures during the development process.

### Utilize Off-the-Shelf/Spare parts for other Projects and Industry Contacts

When time is of the essence the design engineer must utilize the parts that are available and design around them. In order to develop a viable flight worthy mechanism design in an extremely short period of time, it is essential that the proposed design reflect hardware that is available within the development schedule required. Contacts made through association with the Aerospace Mechanism Symposium undoubtedly were crucial to the timely development of the BAM. It was believed that the longest lead item would be the procurement of the actuators and flight qualified electronics. The vendor of the actuators acted extremely quickly and delivered 4 flight units in ~6 weeks. As it turned out, the delivery fit perfectly into the development schedule and did not cause any impact to the development program. The BAM and BAME designs were founded on what was immediately available or easily fabricated with minimal modification of otherwise off the shelf parts.

### Keep it Simple

The old axiom axiom "Keep It Simple" does pay off and was demonstrated in the designs of both the BAM and the BAME. The BAM utilized a basic spur-gear train to provide the required angular resolution to meet the beam steering requirements levied on the BAM. Given the limited command line resources and spare parts available, the extremely simple BAME design proved to be a reliable and robust solution for driving the BAM. The BAM is a good example of a simple yet clever design implementation, executed under a severe time and resource constraint.

## Conclusions

The BAM and BAME components were successfully developed from drawing board concept to flight qualified units in approximately 4 months. Test results indicate that all objectives were met and all requirements verified. The components could have been utilized had they been required. The BAM is a precise, robust mechanism with high torque margins. The beam steering capability of the BAM is excellent. It demonstrated a null stability of  $\pm 2$  arcsec, a repeatable beam steering rate of 0.62 arcsec/step, and a linear range of  $\pm 300$  arcsec. Any future mission with similar requirements to GLAS should seriously consider incorporating a device such as this into the design up front. The risley pair concept provides precise steering capability while not imposing precise alignment requirements of the mechanism to the rest of the system. The risk of adding an additional mechanism must be weighed against the complexity and cost of maintaining extremely tight alignment and stability requirements between the transmit and receive paths of a laser altimeter instrument.

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